Microwave Emission from Aligned Dust

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ABSTRACT

Polarized microwave emission from dust is an important foreground that may contaminate polarized CMB studies unless carefully accounted for. We discuss potential difficulties associated with this foreground, namely, the existence of different grain populations with very different emission/polarization properties and variations of the polarization yield with grain temperature. In particular, we discuss observational evidence in favor of rotational emission from tiny PAH particles with dipole moments, i.e. "spinning dust", and also consider magneto-dipole emission from strongly magnetized grains. We argue that in terms of polarization, the magneto-dipole emission may dominate even if its contribution to total emissivity is subdominant. Addressing polarized emission at frequencies larger than ~ 100 GHz, we discuss the complications arising from the existence of dust components with different temperatures and possibly different alignment properties.

1. Introduction

Diffuse Galactic microwave emission carries important information on the fundamental properties of the interstellar medium, but it also interferes with Cosmic Microwave Background (CMB) experiments (see Bouchet et al. 1999, Tegmark et al. 2000, Efstathiou 2003, this volume). Polarization of the CMB provides information about the Universe that is not contained in the temperature data alone. In particular, it offers a unique way to specifically trace the primordial perturbations of tensorial nature (*i.e.* cosmological gravitational waves, see Seljak & Zaldarriaga 1997, Kamionkowski et al. 1997, Kamionkowski 2003, this volume), and allows one to break some important degeneracies that remain in the measurement of cosmological parameters with intensity alone (Zaldarriaga et al. 1997, Davis & Wilkinson 1999, Lesgourgues et al. 1999, Prunet et al. 2000). Therefore, a number of groups around

the world (see Table 1 in Staggs et al. 1999) work hard to measure the CMB polarization. The first exciting measurements of CMB polarization have recently been reported (Carlstrom 2003, this volume, and Page et al. 2003). The polarization of Galactic emission, long of interest for ISM studies, is now also an important foreground for cosmology.

Among different sources of polarized foregrounds, interstellar dust is probably the most difficult to deal with, for many reasons. First of all, dust has both a population of tiny grains (Leger & Puget 1984), which are frequently called PAH, in addition to the "classical" power-law distribution of larger grains (Mathis, Rumpl & Nordsieck 1977). Then the typical composition of grains changes with their size, with equilibrium temperature depending on both size and composition (Draine & Lee 1984, Finkbeiner et al. 1999). The degree of grain alignment may depend on size and composition, leading to a frequency dependence of the polarization (Hildebrand et al. 2001). Moreover, both recent experience with microwave emissivity and theoretical studies of expected polarization response (Draine & Lazarian 1999) show that the naive extrapolation of the grain properties from FIR to microwave does not work. In addition, in spite of the evident progress achieved by the grain alignment theory (see review by Lazarian 2003), unanswered questions still remain there.

The discovery of the anomalous emission in the range of 10-100 GHz illustrates well the treacherous nature of dust. Until very recently it has been thought that there are three major components of the diffuse microwave Galactic foreground: synchrotron emission, free-free radiation from plasma (thermal bremsstrahlung) and thermal emission from dust. In the microwave range of 10-90 GHz the latter is subdominant, leaving essentially two components. However, it is exactly in this range that an anomalous emission was reported (Kogut et al. 1996a, 1996b). In the paper by de Oliveira-Costa et al. (2002) this emission was nicknamed "Foreground X", which properly reflects its mysterious nature. This component is spatially correlated with 100 μm thermal dust emission, but its intensity is much higher than one would expect by directly extrapolating the thermal dust emission spectrum to the microwave range. Similar surprises may await in the foreground polarimetry data.

In this review, we briefly summarize what is known about the grain populations, grain emission and grain alignment. We discuss the origin of the Foreground X and its expected polarization. Recent reviews of the subject include Draine & Lazarian 1999, Lazarian & Prunet 2002.

2. Observational Evidence

2.1. Infrared emission: extrapolation to microwave range

The emission spectrum of diffuse interstellar dust was mostly obtained by the *InfraRed Astronomy Satellite* (IRAS) and infrared spectrometers on the *COsmic Background Explorer* (COBE) and on the *InfraRed Telescope in Space* (IRTS).

The emission at short wavelength, e.g. < 50 μm, arises from transiently heated very small grains. These grains have such a small heat capacity that the absorption of a single 6 eV starlight photon raises their temperature to $T > 200$K. Typically these grains have less than 300 atoms and can be viewed as large molecules rather than dust particles. They are, however, sufficiently numerous to account for $\sim 35\%$ of the total starlight absorption. The thermal (vibrational) emissivity of these grains is thought to be negligible at low frequency, because they spend most of their time cold, but emit most of their energy when they are hot.

The dominant dust emission above ~ 100 GHz is emission from grains large enough to be in equilibrium with the interstellar radiation field. Emission from this dust peaks at $\sim 140\mu$m and deviates strongly from a thermal blackbody spectrum. A Rayleigh-Jeans emissivity function of ν^2 has often been assumed in the literature (e.g. Draine & Lee 1984, Schlegel, Finkbeiner & Davis 1998) but when dust temperature variation is accounted for, the COBE FIRAS data (Fixsen et al. 1997) are better fit by a steeper power law emissivity ($\beta = 2.6$) near the peak and $\beta = 1.7$ at lower frequencies, with a break at about 500 GHz (Finkbeiner et al. 1999). This fit tied the IRAS and DIRBE data to FIRAS via a fit with only 4 global parameters describing the two emissivity laws, and the requirement that the emission is dominated by grains in equilibrium with the interstellar radiation field. Predictions at $6'$ resolution based on this fit are available on the web.[1]

The two-component model is a substantially better fit (reduced $\chi^2 = 1.85$ compared to 31 for a ν^2 model) even when the spatial and spectral covariance of the FIRAS data (Fixsen et al. 1997) are included (Finkbeiner et al. 1999). And the model is physically plausible: amorphous silicates with a wide range of emissivity indices $\beta \sim 1.2 - 2.7$ have been observed in the lab (Agladze et al. 1996), including amorphous $MgO \cdot 2SiO_2$ which has a very high microwave emissivity to optical absorption ratio, leading to rather different mean temperatures (9K and 16K) for the two components. These lab emissivities were measured at ~ 300 GHz and 20K and may become steeper at lower frequencies. However,

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[1]http://skymaps.info

this interpretation of the spectral break is hardly unique; if the dominant emitter has such a break in its emissivity function at 500 GHz, then a single component could explain the data just as well. Another explanation that has been advanced is very cold dust grains spatially mixed with the warm dust (Reach et al. 1995), though a physical mechanism for keeping the grains so cold is not proposed. Such a model would presumably predict a steeper slope at lower frequencies as well.

Regardless of interpretation, the Finkbeiner et al. (1999) model has been very successful in the sub-mm - microwave, though small but interesting deviations from the model have been observed by BOOMERANG (Masi et al. 2001). At lower frequencies, however, there is a surprise.

Comparing these predictions to COBE DMR, Finkbeiner et al. found that COBE 90 GHz was slightly higher, but at 53 and 31 GHz the emission per dust column is a factor of 2.2 and 31 higher than expected. These results are similar to the earlier Kogut et al. (1996) results derived without an explicit dust temperature correction. Because of this it was expected that the FIRAS-based predictions would agree well with WMAP 94 GHz, but be significantly contaminated by some other dust-correlated emission mechanism at lower frequencies, and this appears to be true. Until this other emission is understood, extrapolation of far IR polarization measurements to the microwave regime will be perilous.

2.2. Anomalous microwave emission

The first detection of anomalous dust correlated emission by COBE (Kogut et al. 1996a, 1996b) was quickly followed by detections in the data sets from Saskatoon (de Oliveira-Costa et al. 1997), OVRO (Leitch et al. 1997), the 19 GHz survey (de Oliveira-Costa et al. 1998), and Tenerife (de Oliveira-Costa et al. 1999, Mukherjee et al. 2000). Initially, the anomalous emission was identified as thermal bremsstrahlung from ionized gas correlated with dust (Kogut et al. 1996a) and presumably produced by photoionized cloud rims (McCullough et al. 1999). This idea was scrutinized in Draine & Lazarian (1997) and criticized on energetic grounds. Poor correlation of Hα with 100 μm emission also argued against the free-free explanation (McCullough et al. 1999). These arguments are summarized in Draine & Lazarian (1999). Recently de Oliveira-Costa et al. (2000) used Wisconsin H-Alpha Mapper (WHAM) survey data and established that the free-free emission "is about an order of magnitude below Foreground X over the entire range of frequencies and latitudes where it is detected". The authors conclude that the Foreground X cannot be explained as free-free emission. Additional evidence supporting this conclusion has come from a study at 5, 8 and 10 GHz by Finkbeiner et al. (2002) of several dark clouds and HII regions, two of which

show a significantly rising spectrum from 5 to 10 GHz.

The recent Wilkinson Microwave Anisotropy Probe (WMAP) data were used to claim a lower limit of 5% for the spinning dust fraction at 23 GHz (Bennett et al. 2003). However, other models of spinning dust are not ruled out by the WMAP data, and in fact fit reasonably well. Finkbeiner (2003) performed a fit to WMAP using only a CMB template, a free-free template (based on Hα correlated emission plus hot gas emission near the Galactic center), a soft synchrotron template traced by the 408 MHz map, a thermal dust extrapolation (Finkbeiner et al. 1999) and a spinning dust template consisting of dust column density times T_{dust}^3. This fit results in excellent χ^2/dof values (1.6,1.09,1.08,1.05,1.08) at (23,33,41,61,94) GHz and a reasonable spectral shape for the average spinning dust spectrum. The whole sky $|b| < 30$ degrees was used where Hα extinction is less than 2 mag, except for point sources, Orion, and NGC5090. The derived emissivities, expressed as Jy/sr^{-1} per H atom for comparison with DL98b, are shown in Fig. 1. Note that there is considerable variation around the sky in the spinning dust spectrum, and Figure 1. shows only the average. The data points *red filled circles* fall somewhat lower than the WNM, CNM, and WIM ISM models and appear flatter, but some superposition of spinning dust models would produce this average spectrum.

This WMAP analysis alone does not rule out the Bennett et al. (2003) hypothesis of hard synchrotron emission, but when combined with the Green Bank Galactic Plane survey data (Langston et al. 2000) at 8 and 14 GHz, spinning dust appears to provide a much better fit than hard synchrotron (Finkbeiner, Langston, & Minter 2003). Some caution is necessary, because the rising ISM spectrum seen from 8 to 14 GHz is observed in the Galactic plane (red stars in Fig. 1), while the WMAP fit is done at higher latitudes; however it is currently a good working hypothesis that spinning dust emission is a substantial contribution to ISM emission at $10 < \nu < 50$ GHz. Other groups analysing WMAP data found more evidence in favor of spinning dust (Hildebrand, private communication, Lagache 2003). For instance, recent results in Hildebrand & Kirby (2003, preprint) on L1622 (one of the clouds observed by Finkbeiner et al. (2002) at 5, 8 and 10 GHz) obtained using WMAP data show a smooth continuation of the spectrum in agreement with the spinning dust model expectations.

2.3. Alignment of Classical Dust

Polarization due to interstellar dust alignment was discovered in the middle of the last century (Hiltner 1949, Hall 1949) and was studied initially via starlight extinction and more recently through emission. Correlation of the polarization with the interstellar magnetic field revealed that electric vector of light polarized via starlight extinction tend to be parallel to
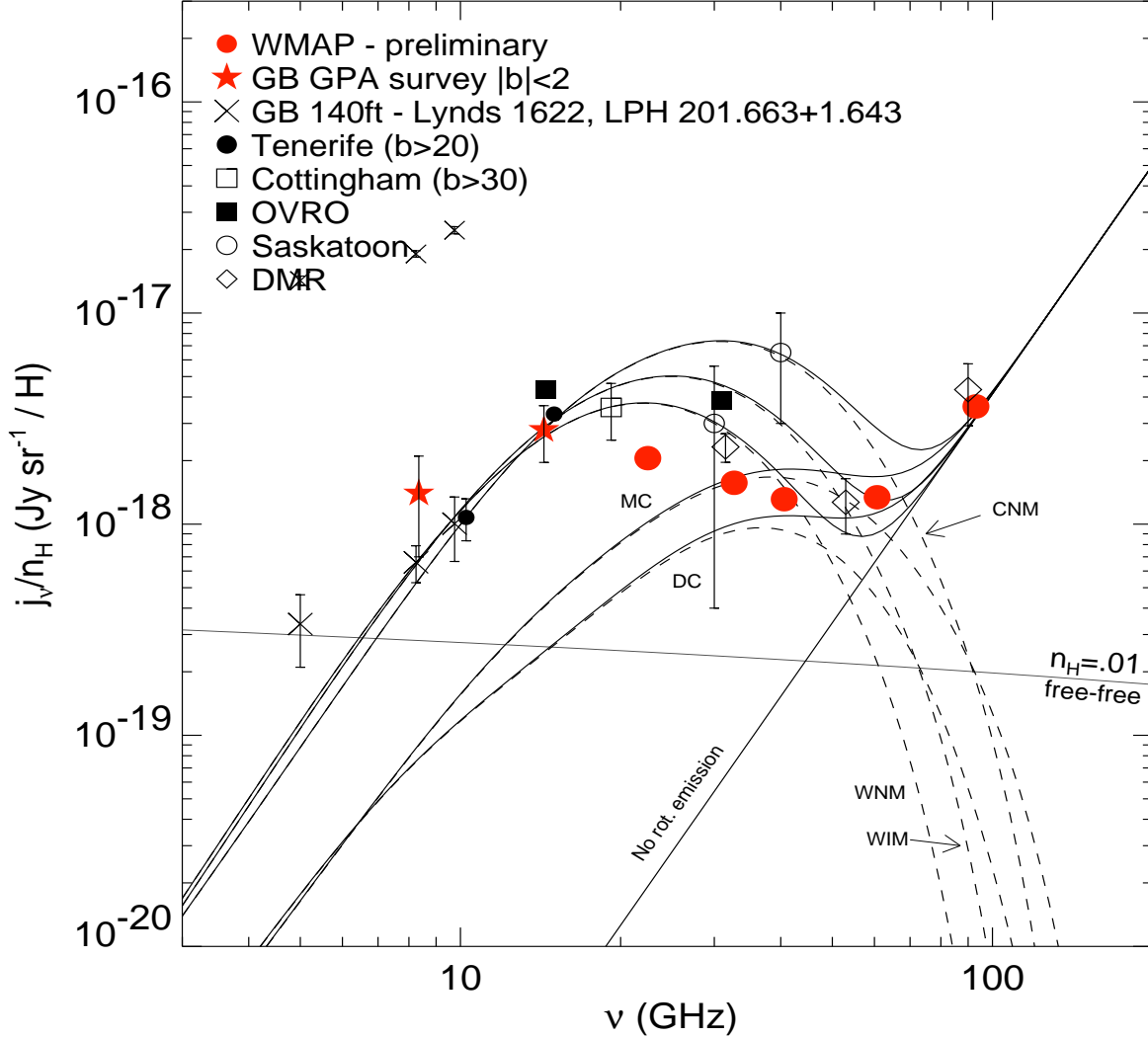
Fig. 1.— Model dust emissivity per H atom for DC, MC, CNM, WNM, and WIM conditions (as in Draine & Lazarian 1998b, Figure 9) with (*solid lines*) and without (*dashed lines*) contribution from vibrational dust at mean temperature. Gray line is emission from free-free for given n_H, or rather $< n_e n_p > / < n_H >$ averaged along the line of sight. Also shown are measurements from the COBE/DMR (*open diamonds*) from Finkbeiner et al. (1999), similar to Kogut et al. (1996); Saskatoon (*open circles*) (de Oliveira-Costa et al. 1997); the Cottingham & Boughn 19.2 GHz survey (*open square*) (de Oliveira-Costa et al. 1998), OVRO data (*solid squares*) (Leitch et al. 1997); Tenerife data (*solid circles*)(de Oliveira-Costa et al. 1999); GB 140 foot (*crosses*)(Finkbeiner et al. 2002), GPA (*red stars*)(Finkbeiner et al. 2003), and WMAP (*red circles*)(Finkbeiner 2003). The OVRO points have been lowered a factor of 3 relative to Draine & Lazarian (1998b, Figure 9), because the unusual dust temperature near the NCP caused an underestimate of the H column density along those lines of sight. In fact, the H columns used in this plot are actually derived from SFD $E(B-V)$ with a conversion factor of 8×10^{21} H / mag. Given the large range of model curves, all measurements are consistent with some superposition of spinning dust, vibrational dust, and

magnetic field[2]. This corresponds to grains being aligned with their longer axes perpendicular to the local magnetic field. Due to the presence of the stochastic magnetic field, the polarization patterns are pretty involved.

The existing data presents a complex picture. It is generally accepted that the observations indicate that the ability to produce polarized light depends on grain size and grain composition. For instance, a limited UV polarimetry dataset available indicates that graphite grains tend not to be aligned (see Clayton et al. 1997), while maximum entropy technique applied to the existing data by Martin & Kim (1995) show that large $> 6 \times 10^{-6}$ cm grains are responsible for the polarization via extinction.

Moreover, the environment of grains seems to matter a lot (Goodman 1995, Lazarian, Goodman & Myers 1997). A study by Arce et al. (1998) indicates that grains selectively extinct starlight up to optical depth $A_v < 3$. Recent emission studies (Hildebrand et al. 1999, 2001) produced a polarization spectrum for dense clouds that reveal a tight correlation between grain temperature and its ability to emit polarized light. As multicomponent fits invoking grains of different temperature were claimed to provide a better fit for the observed 1 mm-100 μm emission (see Finkbeiner, Schlegel & Davis 1999), this correlation may be very troublesome for the attempts to construct polarization templates.

The balloon-borne Archeops mission detects polarization at 353 GHz (850μm) at the level of 4-5%, and over 10% in some clouds (Benoit et al. 2003). This is about the level expected based on polarization of starlight and emission at shorter wavelengths. We eagerly await polarization data from WMAP at $23 - 94$ GHz.

3. Polarized Emission from Classical Dust

The basic explanation of polarized radiation from dust is straightforward. Aligned dust particles preferentially extinct (i.e. absorb and scatter) the E-component of starlight parallel to their longer axis. The E-component of the emitted thermal radiation, on the contrary, is higher along the longer axis. Thus for aligned grains one must have polarization. What is the cause of alignment?

Grain alignment is an exciting and very rich area of research. For example, two new solid state effects have been discovered recently in the process of understanding grain dynamics (Lazarian & Draine 1999, 2000). It is known that a number of mechanisms can provide grain alignment (see review by Lazarian 2000 and Table 1 in Lazarian, Goodman, & Myers 1997).

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[2]The polarizations in emission and in extinction are orthogonal if they are produced by the same grains.

Some of them rely on paramagnetic dissipation of rotational energy (Davis-Greenstein 1951, Purcell 1979, Mathis 1986, Lazarian & Draine 1997, Lazarian 1997a, Roberge & Lazarian 1999) , some appeal to the anisotropic gaseous bombardment when a grain moves supersonically through the ambient gas (Gold 1951, Purcell & Spitzer 1971, Dolginov & Mytrophanov 1976, Lazarian 1994, 1997b, Roberge, Hanany & Messinger 1995, Lazarian & Efroimsky 1996). Many grains are definitely paramagnetic and some may be strongly magnetic. Supersonic grain motions may be due to outflows (Purcell 1969), MHD turbulence (Lazarian 1994, Lazarian & Yan 2002, Yan & Lazarian 2003) or ambipolar diffusion (Roberge & Hanany 1990).

At present, grain alignment via radiative torques (Draine & Weingartner 1996, 1997) looks preferable, although the theory and the understanding of the mechanism are far from being complete (see review by Lazarian 2003). The mechanism appeals to a spin-up of a grain as it differentially scatters left and right polarized photons (Dolginov 1972, Dolginov & Mytrophanov 1976). This process acts efficiently if the irregular grain has its size comparable with the photon wavelength. The mechanism can account for the systematic variations of the alignment efficiency with extinction. However, other mechanisms should also work. For instance, the paramagnetic mechanism may preferentially act on small grains (Lazarian & Martin 2003, in preparation), while mechanical alignment may act in the regions of outflows (Rao et al. 1998). In general, the variety of astrophysical conditions allows various mechanisms to have their niche.

Note that in interstellar environments grain alignment respects the magnetic field orientation, even if the mechanism of alignment is not magnetic in nature. This is because the Larmor precession of grains is so fast compared to the time scales over which either the magnetic field changes its direction or the alignment mechanism acts. In general, the alignment may happen either parallel and perpendicular to the magnetic field. However, in most cases, the alignment happens with long grain axes perpendicular to magnetic field.

Alignment of grains is different in diffuse gas and molecular clouds. Lazarian, Myers & Goodman (1997) showed that in dark clouds without star formation all alignment mechanisms fail. Indeed, grain alignment depends on non-equilibrium processes while interiors of dark clouds are close to thermodynamic equilibrium. As soon as stars are born within clouds, the conditions in their vicinity become favorable for grain alignment. This explains why far infrared polarimetry detects aligned grains, while near infrared and optical polarimetry does not.

We may hope that grain alignment in diffuse clouds is more uniform. Radiation freely penetrates them and therefore the radiative torques must ensure good alignment. This assumption was used by Fosalba et al (2001) to relate the polarization from dust extinction

and the polarization from dust emission. Discussion of this problem is presented in Cho & Lazarian (2003, this volume).

As we have already discussed, grain alignment traces the direction of the local magnetic field. In the presence of turbulence, this field is very complex. It was shown by Cho & Lazarian (2002a) that MHD turbulence can explain the spatial variations of both synchrotron emission and starlight polarization. We note when we deal with dust aligned with a turbulent magnetic field, the resulting polarization depends on the telescope resolution at a particular wavelength. A possible way of dealing with this complication is to correct for the field stochasticity. A tensor description of turbulent magnetic fields was obtained in Cho, Lazarian & Vishniac (2002) and this can be used for this purpose (see also Cho & Lazarian 2002b). The corresponding research should also yield insight into the operation of the Galactic dynamo, high latitude MHD turbulence, and turbulent mixing, and will lead to many yet unforeseen discoveries.

4. Polarized Emission from Spinning Dust

Can the ultrasmall grains observed via Mid-IR be important at the microwave range? The naive answer to this question is no, as the total mass in those grains is small. However, DL98a considered a different mechanism of emission, namely, the rotational emission[3] that must emerge when a grain with a dipole moment μ rotates with angular velocity[4] ω.

For the model with the most likely set of parameters, DL98a obtained a reasonable fit with observations available at that time. It is extremely important that new data points obtained later (de Oliveira-Costa et al. 1998, de Oliveira-Costa et al. 1999) correspond to the already published model. The observed flattening of the spectrum and its turnover around 20 GHz agree well with the spinning dust predictions.

Microwave emission from spinning grains is expected to be polarized if grains are aligned.

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[3]The very idea of grain rotational emission was first discussed by Erickson (1957). More recently, after the discovery of the population of ultrasmall grains, Ferrara & Dettmar (1994) noted that the rotational emission from such grains may be observable, but their treatment assumed Brownian thermal rotation of grains, which is not true.

[4]The calculations in DL98a were questioned by Ragot (2002) who considered the effect of plasma wave drag on spinning dust grains. However, the treatment of ionized particles as a continuous plasma when less than a few particles have chance to interact with the grain over its period does not seem to be right. Moreover, it is possible to show that if it were right, the plasma would not be transparent to microwave emission.

Alignment of ultrasmall grains (essentially large molecules) is likely to be different from alignment of large (i.e. $a > 10^{-6}$ cm) grains. One of the mechanisms that might produce alignment of the ultrasmall grains is the paramagnetic dissipation mechanism of Davis and Greenstein (1951). The Davis-Greenstein alignment mechanism is straightforward: for a spinning grain the component of interstellar magnetic field perpendicular to the grain angular velocity varies in grain coordinates, resulting in time-dependent magnetization, associated energy dissipation, and a torque acting on the grain. As a result grains tend to rotate with angular momenta parallel to the interstellar magnetic field.

Lazarian & Draine (2000, henceforth LD00) found that the traditional picture of paramagnetic relaxation is incomplete, since it disregards the so-called "Barnett magnetization" (Landau & Lifshitz 1960). The Barnett effect, the inverse of the Einstein-De Haas effect, consists of the spontaneous magnetization of a paramagnetic body rotating in field-free space. This effect can be understood in terms of the lattice sharing part of its angular momentum with the spin system. Therefore the implicit assumption in Davis & Greenstein (1951)– that the magnetization within a *rotating grain* in a *static* magnetic field is equivalent to the magnetization within a *stationary grain* in a *rotating* magnetic field – is clearly not exact.

LD00 accounted for the "Barnett magnetization" and termed the effect of enhanced relaxation arising from grain magnetization "resonance relaxation". It is clear from Fig. 2 that resonance relaxation persists at the frequencies when the Davis-Greenstein relaxation vanishes. However the polarization is marginal for $\nu > 35$ GHz anyhow. The discontinuity at ~ 20 GHz is due to the assumption that smaller grains are planar, and larger grains are spherical. The microwave emission will be polarized in the plane perpendicular to magnetic field.

Can we check the alignment of ultrasmall grains via infrared polarimetry? The answer to this question is "probably not". Indeed, as discussed earlier, infrared emission from ultrasmall grains, e.g. 12 μm emission, takes place as grains absorb UV photons. These photons raise grain temperature, randomizing grain axes in relation to its angular momentum (see Lazarian & Roberge 1997). Taking values for Barnett relaxation from Lazarian & Draine (1999), we get the randomization time of the 10^{-7} cm grain to be 2×10^{-6} s, which is less than the grain cooling time. As a result, the emanating infrared radiation will be polarized very marginally. If, however, Barnett relaxation is suppressed, the randomization time is determined by inelastic relaxation (Lazarian & Efroimsky 1999) and is ~ 0.1 s, which would entail a partial polarization of infrared emission.
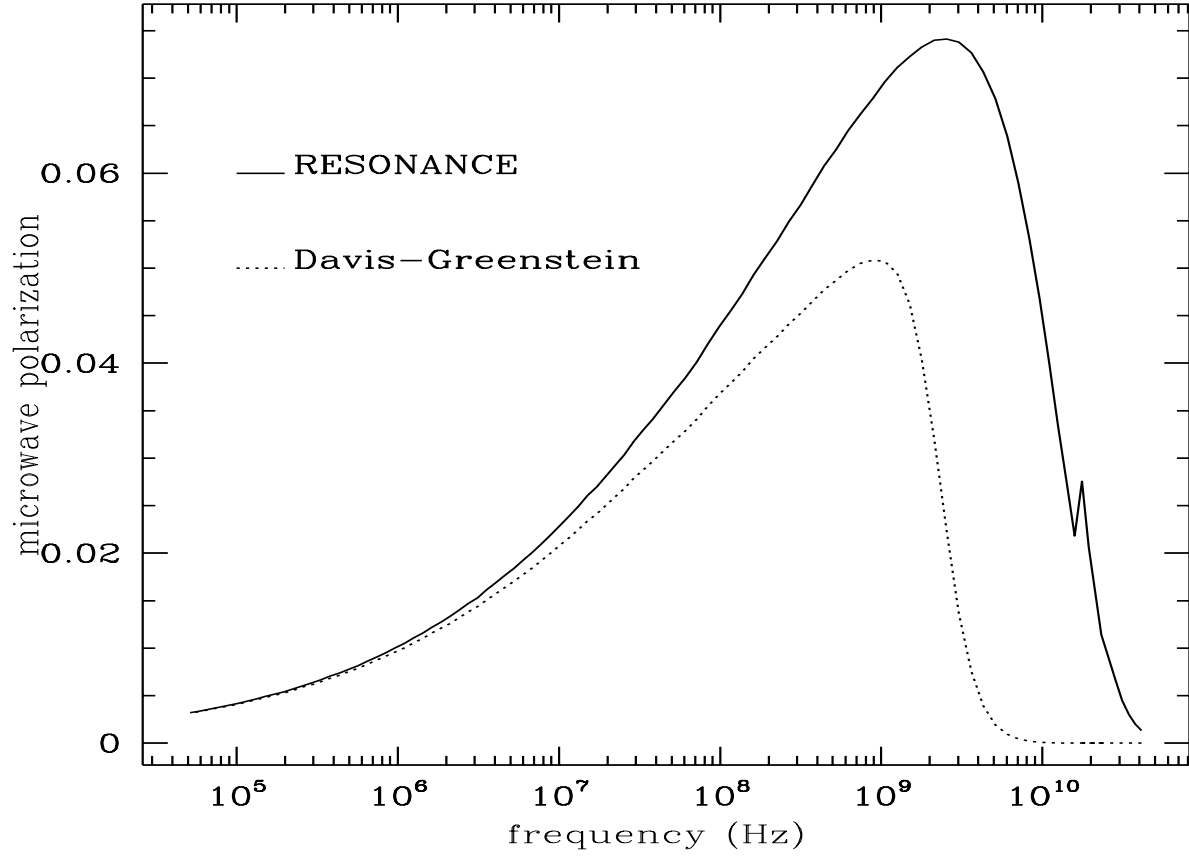
Fig. 2.— Polarization for both resonance relaxation and Davis-Greenstein relaxation for grains in the cold interstellar medium as a function of frequency (from LD00). For resonance relaxation the saturation effects (see eq. (1)) are neglected, which means that the upper curves correspond to the *maximal* values allowed by the paramagnetic mechanism.

5.   Polarized Emission from Magnetic Grains

While the spinning grain hypothesis got recognition in the community, the magnetic dipole emission model suggested by Draine & Lazarian (1999, henceforth DL99) was left essentially unnoticed. This is unfortunate, as magnetic dipole emission provides a possible alternative explanation for the Foreground X. Magnetic dipole emission is negligible at optical and infrared frequencies. However, when the frequency of the oscillating magnetic field approaches the precession frequency of electron spin in the field of its neighbors, i.e. 10 GHz, the magneto dipole emissivity becomes substantial.

How likely is that grains are strongly magnetic? Iron is the fifth most abundant element by mass and it is well known that it resides in dust grains (see Savage & Sembach 1996). If 30% of grain mass is carbonaceous, Fe and Ni contribute approximately 30% of the remaining grain mass. Magnetic inclusions are widely discussed in grain alignment literature (Jones & Spitzer 1967, Mathis 1986, Martin 1995, Goodman & Whittet 1996). If a substantial part of this material is ferromagnetic or ferrimagnetic, the magneto-dipole emission can be comparable to that of spinning grains. Indeed, calculations in DL99 showed that less than 5% of interstellar Fe in the form of metallic grains or inclusions is necessary to account for the Foreground X at 90 GHz, while magnetite, i.e. Fe_3O_4, can account for a considerable part of the anomalous emissivity over the whole range of frequencies from 10 to 90 GHz. Adjusting the magnetic response of the material, i.e. making it more strongly magnetic than magnetite, but less magnetic than pure metallic Fe, it is possible to get a good fit for the Foreground X (DL99).

How can magneto-dipole emission be distinguished from that from spinning grains? The most straightforward way is to study microwave emission from regions of different density. The population of small grains is depleted in dark clouds (Leger and Puget 1984) and this should result in a decrease of contribution from spinning grains. Private communication from Dick Crutcher who attempted such measurements corresponds to this tendency, but the very detection of microwave emissivity is a 3σ result. Obviously the corresponding measurements are highly desirable. As for now, magnetic grains remain a strong candidate process for producing part or even all of Foreground X. In any case, even if magnetic grains provide subdominant contribution, this can be important for particular cases of CMB and interstellar studies. For instance, polarization from magnetic grains may dominate that from spinning grains even if the emission from spinning grains is more of higher level.

The mechanism for producing polarized magneto-dipole emission is similar to that producing polarization of electro-dipole thermal emission emitted from aligned non-spherical grains (see Hildebrand 1988). There are two significant differences, however. First, strongly magnetic grains can contain just a single magnetic domain. Further magnetization along the

axis of this domain is not possible and therefore the magnetic permeability of the grains gets anisotropic: $\mu = 1$ along the domain axis, and $\mu = \mu_\perp$ for a perpendicular direction. Second, even if a grain contains tiny magnetic inclusions and can be characterized by isotropic permeability, polarization that it produces is orthogonal to the electro-dipole radiation emanating through electro-dipole vibrational emission. In case of the electro-dipole emission, the longer grain axis defines the vector of the electric field, while it defines the vector of the magnetic field in case of magneto-dipole emission.

The results of calculations for single domain iron particle (longer axis coincides with the domain axis) and a grain with metallic Fe inclusions are shown in Fig. 3. Grains are approximated by ellipsoids $a_1 < a_2 < a_3$ with $\mathbf{a_1}$ perfectly aligned parallel to the interstellar magnetic field $\mathbf{B}$. The polarization is taken to be positive when the electric vector of emitted radiation is perpendicular to $\mathbf{B}$; the latter is the case for electro-dipole radiation of aligned grains. This is also true (see Fig. 3) for high frequency radiation from single dipole grains. It is easy to see why this happens. For high frequencies $|\mu_\perp - 1|^2 \ll 1$ and grain shape factors are unimportant. The only important thing is that the magnetic fluctuations happen perpendicular to $\mathbf{a_1}$. With $\mathbf{a_1}$ parallel to $\mathbf{B}$, the electric fluctuations tend to be perpendicular to $\mathbf{B}$ which explains the polarization of single domain grain being positive. For lower frequencies magnetic fluctuations tend to happen parallel to the intermediate size axis $\mathbf{a_2}$. As the grain rotates about $\mathbf{a_1}\|\mathbf{B}$, the intensity in a given direction reaches maximum when an observer sees the $\mathbf{a_1 a_2}$ grain cross section. Applying earlier arguments it is easy to see that magnetic fluctuations are parallel to $\mathbf{a_2}$ and therefore for sufficiently large a_2/a_1 ratio the polarization is negative. *The variation of the polarization direction with frequency presents the characteristic signature of magneto-dipole emission from aligned single-dipole grains and it can be used to separate this component from the CMB signal.* Note that the degree of polarization is large, and such grains may substantially interfere with attempts at CMB polarimetry. Even if the intensity of magneto-dipole emission is subdominant to that from rotating grains, it can still be quite important in terms of polarization. A relatively weak polarization response is expected for grains with magnetic inclusions (see Fig. 3). The resulting emission is negative as magnetic fluctuations are stronger along longer grain axes, while the short axis is aligned with $\mathbf{B}$.

Systematic studies of dust foreground polarization should improve our insight into the formation dust, its structure, its composition. For instance, DL99 showed that the present-day microwave measurements do not allow more than 5% of Fe to be in the form of metallic iron. More laboratory measurements of microwave properties of candidate materials are also necessary. Some materials, e.g. iron, were studied at microwave range only in the 1950's and this sort of data must be checked again using modern equipment.
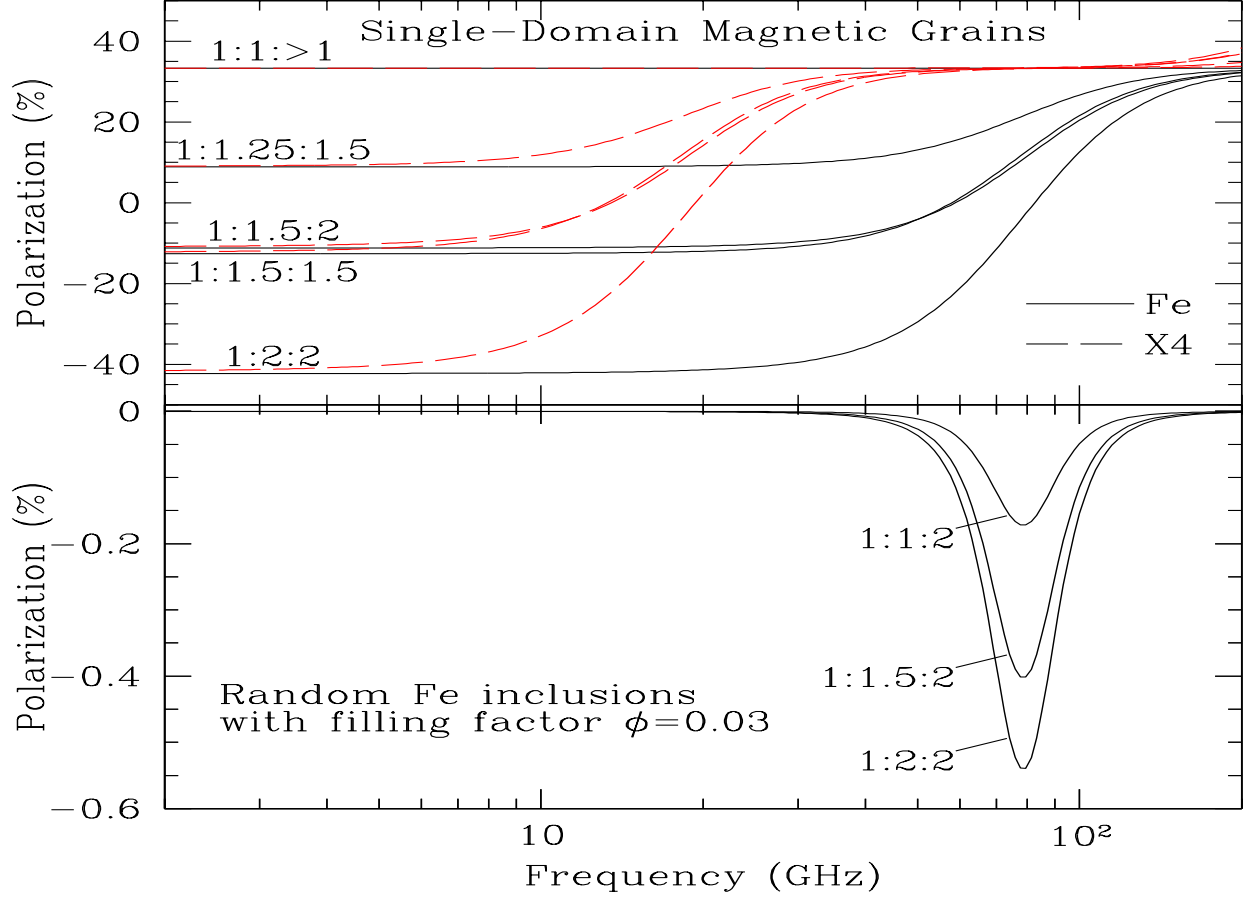
Fig. 3.— Polarization from magnetic grains (from DL99). Upper panel: Polarization of thermal emission from perfectly aligned single domain grains of metallic Fe (solid lines) or hypothetical magnetic material that can account for the Foreground X (broken lines). Lower panel: Polarization from perfectly aligned grains with Fe inclusions (filling factor is 0.03). Grains are ellipsoidal and the result are shown for various axial ratios.

6. Summary

The principal points discussed above are as follows:

- Dust provides the most intricate pattern of polarized radiation. The dependence of polarization of grain temperature, composition, size and environment makes the use of templates difficult.

- If anomalous emission in the range of 10-100 GHz is due to spinning dust particles, the polarization of the emission is marginal for frequencies larger than ~ 35 GHz. If the anomalous emission or part of it is due to magneto-dipole mechanism the polarization may be substantial and may exhibit reversals of direction with frequency.

- To get a better insight into the microwave properties of dust more laboratory studies are necessary. Some of them, e.g. measurements of the magnetic susceptibility of candidate materials at microwave frequencies, are straightforward using the modern technology.

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